On the Design of Integrated Tele-Monitoring/ Operation System for Therapeutic Devices in Isolation Intensive Care Unit

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***Abstract*—We design a central controller system (CCS) and a tele-controlled system (TCS) with an aim of developing the integrated tele-monitoring/operation system that can enable the medical staff to tele-monitor the state of therapeutic devices utilized in the isolation intensive care unit (ICU) and to tele-operate its user interfaces. To achieve this aim, we survey the medical staff for medical requirements first and define the design guideline for tele-monitoring/operation functionality and field applicability. In designing the CCS, we focus on realizing the device having intuitive and user-friendly interfaces so that the medical staff can use the device conveniently without pre-training. Further, we attempt to implement the TCS capable of manipulating various types of user interfaces of the therapeutic device (e.g., touch screen, buttons, and knobs) without failure. As two core components of the TCS, the precision XY-positioner having a maximum positioning error of about 0.695 mm and the end-effector having three-degrees-of-freedom motion (i.e., pressing, gripping, and rotating) are applied to the system. In the experiment conducted for assessing functionality, it is investigated that the time taken to complete the tele-operation after logging into the CCS is less than 1 minute. Furthermore, the result of field demonstration for focus group shows that the proposed system could be applied practically to the medical fields when the functional reliability is improved.**

***Index Terms*—Medical robots and systems, robot-assisted telemedicine, telerobotics and teleoperation.**

I. Introduction

FROM the outbreak of COVID-19, people in the world have been constantly threatened. World Health Organization (WHO) reports cumulative data of over 500 million confirmed cases and over 6 million deaths worldwide [1]. Because many confirmed cases of COVID-19 show serious symptoms including complications of various diseases, about one-third of patients had been admitted to intensive care unit (ICU), of which the reported mortality rate had been 39% [2]. In medical fields, medical staff show concerns about dangers and discomforts within therapeutic processes. Medical staff in ICU wear personal protective units (PPEs) to minimize hazards of contamination. Every time they handle situations in ICU, medical staff need to don and doff PPE even for a simple medical action. Accordingly, numerous staff feel arduous about the frequent wearing of PPE and anxious about the scarcity of PPE [3]. Even though medical staff fight infections, they have high infectious risks [4], and thousands of their deaths have been globally reported until May 2021 [5]. Medical staff also feel physical and psychological burdens and many of them appeal burnouts from working in critical care [6].

To challenge the COVID-19 pandemic situation, robots are highlighted as they can bridge physical disconnections and provide a shield against infection [7]. An automatic temperature measuring robot was developed to provide a safe diagnosis from non-contact infrared scanning [8]. Sample collecting robots have also been developed [9]. Other technologies cover delivery services, disinfection, and telecommunication [10]. Especially in medical environments, robots are becoming a strong solution for reducing the risk of contamination [11], [12]. Autonomous mobile robots can conduct disinfection tasks in hospitals [13]. Tele-operational robotic system that can perform lung ultrasound scanning tasks was developed [14].

Because the treatments for COVID-19 are conducted inside isolation ICUs, remote control of therapeutic devices has been highlighted to support medical staff [15]. A tele-operated robot system equipped with a dual-arm manipulator was developed to conduct various medical tasks [16]. Still, developed tele-operative platforms need to occupy smaller spaces in ICU and conduct tasks more accurately and rapidly. *Vagvolgyi et al.* developed a tele-robotic system to remote control the mechanical

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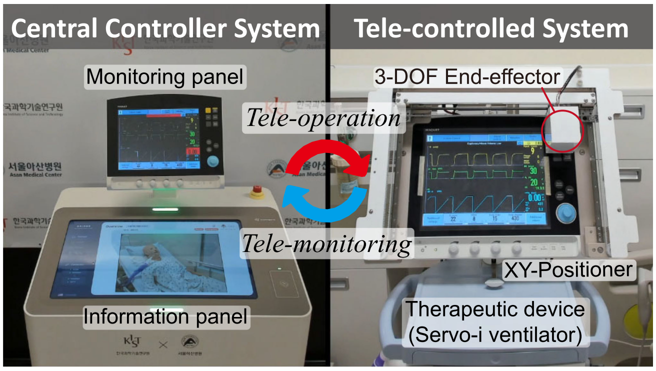

Fig. 1. Overview of the proposed tele-monitoring/operation system.

ventilator Maquet Servo-u [17]. They developed a patient side system consisting of a ventilator-mounted 2-axis gantry system as a positioner and end-effector to press the touch panel. Also, they used a portable tablet console to tele-operate the patient side system. The system resulted in tele-operation latency of 28 seconds which is reduced by 3.8 times compared with manual operation (108 seconds, including donning and doffing PPE), and recorded average positioning accuracy of 5.94 mm, repeatability of 7.5 mm.

In this work, we propose the design concept for an integrated robotic system that can perform tele-monitoring and tele-operation of therapeutic devices in isolation ICU. To demonstrate the practicability of our proposed concepts, we develop central controller system (CCS) and tele-controlled system (TCS) for a target therapeutic device (Fig. 1). Using the design principles proposed in this letter, tele-robotic systems that can serve as an independent and secure channel for other therapeutic devices can also be comparably developed.

The main contributions of this study are as follows.

1) Design of the tele-monitoring/operation system based on engineering specifications derived from medical requirements of medical staff working in ICUs.
2) Implementation of precision TCS consisting of H-frame XY-positioner and three-degrees-of-freedom (3-DOF) end-effector capable of manipulating various types of user interfaces (UIs) of therapeutic devices.
3) UI/UX design for the kiosk-typed CCS that is intuitive and user-friendly for the medical staff to use without pre-training.
4) Demonstration of functionality and applicability of the integrated system based on the user test with a focus group comprised of medical staff.

II. Medical Requirements and Development Scheme

Among complications of COVID-19, the most prominent diseases are respiratory diseases such as viral pneumonia [18]. Furthermore, among therapeutic devices in ICU, mechanical ventilators are known to be the most frequent source of alarms [19]. Responding to the most urgent need for remote control, we chose a mechanical ventilator as our first target device to aid critical care in isolation ICU. Furthermore, Maquet Servo-i (*Gentinge*), is chosen because Servo-i has been the most used model in ICUs of South Korea [20].

To develop a system that can be used in a safe and straightforward manner, we received valuable comments from medical staff working in Asan Medical Center (AMC), Seoul, South Korea. From their expertise and experiences in ICU, medical staff requested that the tele-robotic system to have the functions they really need.

TABLE I
Medical Requirements

Functionality	
Tele-monitoring	· Monitoring patients' data from therapeutic devices without any loss (e.g., vital signal, operation records) · Data acquisition from therapeutic devices and storage in CCS · Checking patients through a patient monitoring camera · Detection of emergency situations and alarm feedback · Telecommunication between staff inside and outside of ICU
Tele-operation	· Reliable tele-operability with zero-failure · Short latency of tele-operation · Fast and simple transition between manual-/tele-operation mode · Emergency stop button for integrated system · Feedback about the working condition of TCS · Compact end-effector not blinding the tele-monitored display
Usability	
Controll-ability	· Accessibility only to authorized medical staff for data security · Correcting recognized maloperation during tele-operation · User-friendly UI/UX (training-free)
Field-applicability	· Multiple TCSs connected to a single CCS · Sterilizability and disinfectability · Employment of secure communication protocols · Built-in uninterruptible power supply (UPS)

One of the most desired functions is tele-monitoring. Despite physical barriers between ICU and nurse station, nurses need to irregularly check the respiratory status of patients, especially those in critical states. Using tele-monitored data, medical staff can double-check the patient's current condition and determine whether further action is required. The monitored data further need to be saved in storage and used as evidence for medical accidents. Regarding tele-operation of therapeutic devices, medical staff insisted that reliable operation of the system is crucial rather than real-like fast operation because malfunction can lead to serious medical accidents. In addition, a simple transition from tele-operation mode to manual mode was requested from medical staff because manual operation mode should be supported for various medical protocols. Lastly, as the system is in environments frequently exposed to viruses, it should endure disinfection procedures. Other detailed medical requirements are categorized in terms of functionality and usability in Table I.

In connection with the medical requirements, we set developmental goals to fulfill the requirements. For designing a CCS, we aim to provide an identical feeling of usage and implement an intuitive software user interface. Medical staff can also browse the history of operational command. For sensory feedback, light-emitting diode (LED) and speaker indicate various medical situations. Furthermore, to ensure the security of medical actions, medical staff use their identification card to log in. For a TCS, we aim to implement an accurate and precise motion for highly reliable tele-operation. The success rate of tele-operation can be set by considering periodical maintenance of therapeutic devices. To be easily switched to manual operation mode, the mechanism is designed to be backdrivable. Furthermore, medical staff can promptly detach the TCS for every contingency that the system is out of order. Lastly, the entire structure of the TCS is designed to have an exterior cover to be easily sterilized.

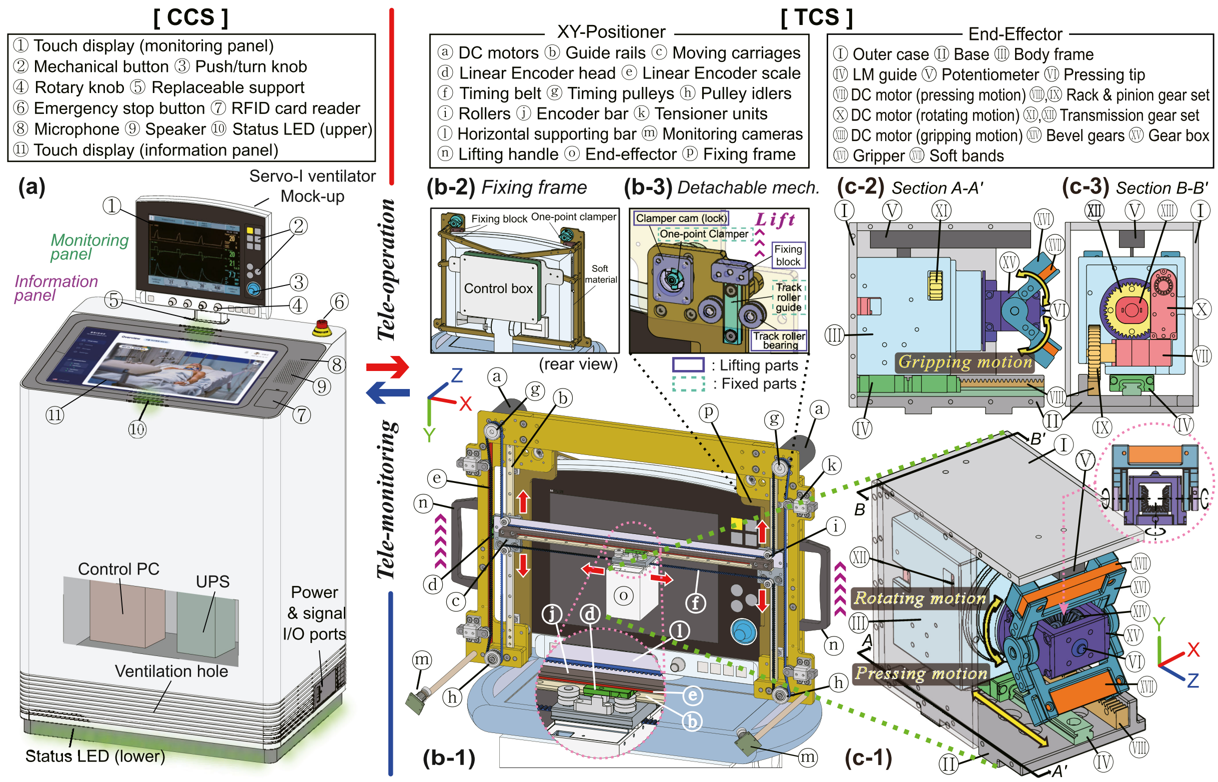

Fig. 2. Configuration and design of the proposed tele-monitoring/operation system. The integrated system consists of a CCS indicated in (a) and the TCS which includes XY-Positioner and 3-DOF end-effector indicated in (b-1) and (c-1), respectively. (b-2) shows the configuration of fixing frame attached to the target therapeutic device (i.e., Servo-i ventilator). (b-3) indicates configuration of the detachable mechanism. (c-2) and (c-3) show the cross-section views of the 3-DOF end-effector in YZ-plane and XY-plane, respectively.

III. Design Considerations for Integrated System

As mentioned above, the prior research [17] introduced the tele-robotic system for the touchscreen controlled mechanical ventilator. In designing the integrated system in this study, we aim to enhance the working performances and usability of the system to meet the medical requirements. Although the prior research used a portable tablet to tele-operate the patient side system, we develop the kiosk-typed central system. The central system consists of intuitive user interfaces, supports secure medical actions, and provides audible feedback for emergency situations. Also, operation history is saved as log data in kiosk PC. For TCS, the prior research developed a patient side system that is controlled by visual servoing algorithm. Whereas we develop the mechanically stable tele-controlled system having precise positioning performance that does not need to be calibrated when turned on. Further, we design the compact and lightweight 3-DOF end-effector to manipulate common user interfaces (i.e., touch panel, buttons, and knobs) typically comprised in most therapeutic devices.

A. Central Controller System (CCS)

The CCS performs as an intuitive and user-friendly interface (Fig. 2(a)). A monitoring panel, which is an upper part of the CCS, is designed to be identical to the head of Servo-i and have the same height (1.3 m) as Servo-i for convenient use of medical staff. Thus, medical staff do not need any additional pre-training to operate the CCS. A 12.1-inch resistive touch screen is installed inside the monitoring panel. It displays tele-monitored data by replotting and reconstructing the transmitted data from the communication port of the ventilator. Further, the touch position is transmitted to the TCS as an input command as shown in Fig. 3(b). The rotary encoders and mechanical switches embedded in the monitoring panel send manipulation command. A connecting part between the monitoring panel and information panel of the CCS is designed as replaceable support that can be simply replaced with other monitoring panel to use other therapeutic devices.

An information panel, the lower part of the CCS, supports secure and intuitive tele-monitoring/operation of therapeutic devices. A 24-inch capacitive touch screen displays a graphical user interface (GUI) designed with commercial program (Qt Designer 5, *The Qt Company*). A graphical user scenario is shown in Fig. 3(a) to illustrate the steps for remote control using the GUI in an emergency situation. If an emergency situation happens, it is detected through the communication port of the mechanical ventilator. Multi-colored LEDs and a speaker provide sensory alerts to display the medical situation to medical staff. The LEDs are attached to the upper and bottom sides of the CCS so that medical staff can recognize the situation from a distance. For secure medical actions, an RFID reader is used to identify authorized medical staff. After tagging RFID, users can select patients whom they want to tele-monitor/operate in the designed GUI. While tele-controlling the ventilator, users can also check the patient monitoring video. As operation starts, every command is stored in the control PC of CCS to be used as research data and legal materials. Users can browse the operation

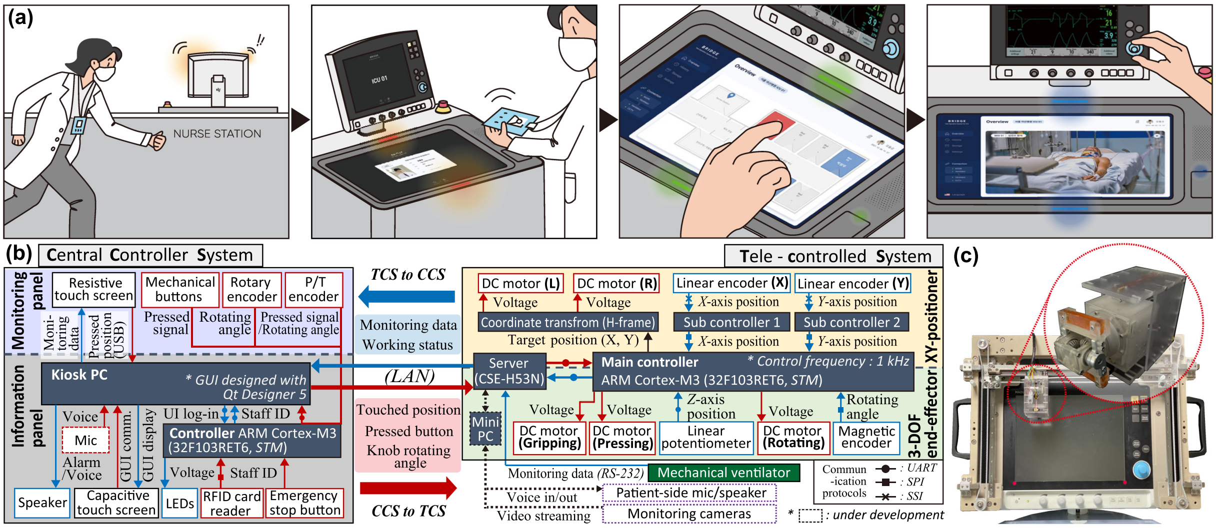

Fig. 3. (a) indicates graphical user scenario. The illustrations show the tele-monitoring/operation protocol: emergency alert, RFID card tag and log in, patient identification, and tele-operation/monitoring for medical situations. (b) presents schematic diagram of overall data flow of the integrated system. (c) shows functional prototype of the tele-controlled system.

history to see what happened in each ICU and how the staff handled it. An emergency stop button is installed on the upper side of the kiosk for every contingency that the TCS malfunctions. When the button is pressed, the TCS stops immediately and medical staff can manipulate the system manually. Inside the CCS, UPS is placed in case of power failure.

B. Tele-Controlled System (TCS): XY-Positioner

From the developmental scheme, we aim to develop a modular-type XY-positioner that can faultlessly transport the end-effector to the target interface. Typical 2-DOF positioner mechanisms include delta robot, SCARA robot, and belt-driven mechanisms. Delta mechanism, although shows highly accurate motion and has 3-DOF, is hard to be stably installed upon therapeutic devices and blinds a large portion of the display that needs to be tele-monitored. SCARA configuration has a singularity problem and can only utilize a certain portion of the entire workspace. In addition, it has a large moving mass that needs to be compensated. Conventional 2-axes gantry systems with ball/lead screws have bulky and heavy structures that cannot be easily mounted. Also, screw–driven structures have low backdrivability, making it difficult for medical staff to manually operate. Recently, belt-driven mechanisms, such as T-bot, H-bot (also referred to as H-frame), and Core-XY type, are widely used. T-bot gantry has a simple structure, but it can outreach over the boundary of therapeutic devices. Core-XY is also a stable platform, but it has double-layer belt transmission that is prone to having different belt tension, which can degrade the positioning precision of the mechanism.

H-frame architecture [21] is a simple, precise parallel belt-driven structure having an H-shaped belt configuration. The vertically translating mass of the H-frame structure is relatively light, making it suitable for tele-controlled therapeutic devices with a common vertical tilting posture. Still, it is susceptible to parasitic torsional skew of long, traversing components when it accelerates and changes directions. This problem can be solved by inserting a rigid part that can withstand the torsional moment of the structure. To implement simple-structured, and mechanically precise motion, we select H-frame as an operating principle of our TCS.

In designing the positioner, we first design the fixing frame that can provide a stable ground that interconnects the therapeutic device and the positioner module (Fig. 2(b-2)). The gap between the fixing frame and the therapeutic device is filled with soft materials (VytaFlex-20, *Smooth-On*) to be tightly fitted. The material used for fixing frame and outer frame of the positioner is selected as Polyether ether ketone (PEEK) considering its superior mechanical properties such as hardness-to-weight ratio.

The overall structure of the XY-positioner is designed to be compact (Fig. 2(b-1)). The transmission consists of pulleys, pulley idlers, rollers, tensioner units, and S3M timing belt. Horizontal moving parts include two components: a horizontal plate that increases the second moment of inertia in Z-axis and an encoder bar on which a horizontal encoder scale is attached. Even though stepper motors are widely used for cartesian motions, they are prone to lose steps in dynamic conditions and their torque capacity drops rapidly with increasing speed. To implement precise and fast motion, our 2-DOF positioner is driven by 2 geared DC motors (PG42-RS555PW-2882E, *Motorbank*), with position feedback from 2 absolute linear magnetic encoders (AKS17 w/ LMS3, *Bogen*), using a linear guide set (GV3, *Hepco*). To move the H-frame structure, motor driving signals are calculated by coordinate transform and proportional-integral-derivative (PID) control algorithm with 1 kHz of control frequency.

A simple pre-calibration is performed to match the actual position of the target interface of the ventilator with the input positioning command from the monitoring panel. First, we record the 2-dimensional position of main landmarks of the ventilator (i.e., endpoints of touch screen, central points of buttons and rotary knobs) based on the linear encoder counts used in the XY-positioner. For positioning command from the touch display, the command input undergoes linear mapping by multiplying scaling factor. In this way, the positioning command is converted into the linear encoder data values. According to a manipulation signal from the mechanical button and/or rotary encoder, the XY-positioner moves to the recorded position of the target interface. This pre-calibration process is required only once before applying the system to the ventilator. To be promptly detached from the therapeutic device, the TCS has track roller set and one-point clamper (QCTHA, *IMAO*) on its rear side (Fig. 2(b-3)). Track roller bearings (LFR50-5-6-KDD, *JESA*) and track roller guides are used to stably fix the positioner module. When detaching the TCS, the user can simply unlock 2 one-point clampers at the rear side and lift the TCS using lifting handles. The functional prototype of the entire tele-controlled system is shown in Fig. 3(c).

To further develop the practical method of tele-monitoring the ventilator's screen, two camera modules (see Fig. 2(b-1)) can be installed on a standing bar fixed to the bottom of the positioner. Otherwise, the screen of ventilator might be obstructed as it may interfere with manual operation.

C. Tele-Controlled System (TCS): 3-DOF End-Effector

The end-effector, which is attached to the carriage of the XY -positioner, is designed to manipulate the various physical interfaces (i.e., touch screen, buttons, and rotary knobs) of therapeutic devices. Because therapeutic devices are manipulated by pressing, gripping, and rotating motions, the end-effector is designed to have 3-DOF for each motion. In designing the end-effector, we focus on 2 major considerations. First, the end-effector has to be compact. Because it is fixed upon the carriage of the XY-positioner, an increase in size and weight causes the deflection and mechanical vibration of the positioner components. In addition, because the entire structure of the end-effector blinds displays of the therapeutic device, the large size of the end-effector can disturb medical staff to tele-monitor the therapeutic device. For the compact design, we utilize minimal necessary components to implement 3 degrees of freedom. Secondly, the end-effector needs to be adaptable to various sizes and shapes (e.g., cylindrical shapes and circular truncated cones) of physical interfaces of therapeutic devices.

We design the functional prototype of the 3-DOF end-effector. The structural configuration is schematized in Fig. 2(c-1). Most parts of the end-effector, including a base, gears, a body frame, and an outer case, are 3D-printed to reduce the weight of the end-effector. For the pressing motion, rack and pinion gear set with DC motor are utilized to make a fast linear motion. A linear motion guide (SSE2BS8-70, *MISUMI*) is placed next to the gear set to prevent parasitic motions during pressing motion. A linear potentiometer is installed on the opposite side of the outer case to detect linear displacement of the end-effector. At the head of the end-effector, a pressing tip is used to tap the screen and buttons.

Second, for the gripping motion, we match the central axes of pressing motion and gripping motion to increase the controllability of physical interfaces. A high-torque DC motor and 3 bevel gears are combined to convert the rotary motion of the DC motor to angular gripping motion. When the DC motor rotates, jaws connected to the side bevel gears have a bi-directional angular motion to grip objects as shown in Fig. 2(c-2). Because the knobs embedded in the ventilator have different diameters as 12.5 mm and 17.5 mm, we design the band-shaped gripper-ends with a soft material (Vytaflex 20, *Smooth-On*) as shown in Fig. 2(c-1). When the gripper grips the knob, the band stretches and so adapts to the size of knobs so that the contact area between the bands and knobs increases. Therefore, the knob can be gripped firmly.

Finally, for the rotating motion, a DC motor with a magnetic encoder and a 3D-printed custom spur gear is utilized to make the rotary motion of the gripper. The small DC motor for gripping motion is centered in the spur gear as shown in Fig. 2(c-3) and the gear is connected to the gripper. In this way, the DC motor for rotary motion rotates the gripping part after gripping motion. The magnetic encoder attached to the back of the DC motor detects angular displacement of the motor and is utilized to control the angular position of the gripping part.

D. Integration of CCS and TCS

UI manipulation commands (i.e., touch screen input, pressed button, and rotated encoder) are transmitted from PC in CCS to TCS. As tele-operation tasks are completed, the feedback about the working status of the tele-controlled system is transmitted from TCS to CCS. Encrypted local area network protocol can be used in medical environments and its feasibility is demonstrated with the intranet of AMC. Using ethernet to RS-232 converting server (CSE-53N, *Sollae Systems*), each TCS is assigned an individual IP address and connected to the CCS. A schematic diagram for the architecture of overall data flow is presented in Fig. 3(b).

IV. Experimental Assessment of Working Performances

To verify the tele-operability of the proposed system, experiments for measuring the system's working performances are conducted. The operational performances of XY-positioner and 3-DOF end-effector are investigated. In addition, the latency of the integrated system is counted.

A. Working Performance of XY-Positioner

For the XY-positioner, the most important role is to accurately and rapidly carry the end-effector to target physical interfaces. All experiments are conducted under the steepest fixing angle of the ventilator, which is 76 degrees. Experimental data are collected using the linear encoders, for torsional racking of horizontal bar is negligible and both fixing frame and detachable mechanism provide a stable ground between the target device and the positioner. Additionally, experiments are done without the end-effector to evaluate the individual performance of the positioner.

First, positioning accuracy and repeatability of the positioner are evaluated. To evaluate the positioning performance over the entire working area, the data set of target points and actually arrived positions are recorded (Fig. 4(b)). The positioner translates to 99 points (11 and 9 for the X- and Y- axis, respectively) in random sequence. The positioner repeats this for 10 cycles, collecting 990 positioning data in total. For 990 points, the average Euclidean error between the target position and actual position is 99 μm, and average errors in *X*- and *Y*-axis are -7 μm and 61 μm, respectively. Maximum Euclidean errors for every 99 points are plotted in Fig. 4(a), which is overlapped with the figure of Servo-i ventilator in actual size. Among 990 data, 695 μm is the maximum recorded Euclidean error. Positioning repeatability is also calculated using ISO 9283-1998 standard [22], which is 348 μm. Considering that the smallest physical interface of the Servo-i, white rotary knob, has a 12mm diameter, the positioner has the capability of providing exact manipulating conditions for the 3-DOF end-effector. Namely, the positioner does not allow the end-effector to make eccentric rotation nor press adjacent buttons and touch interfaces.

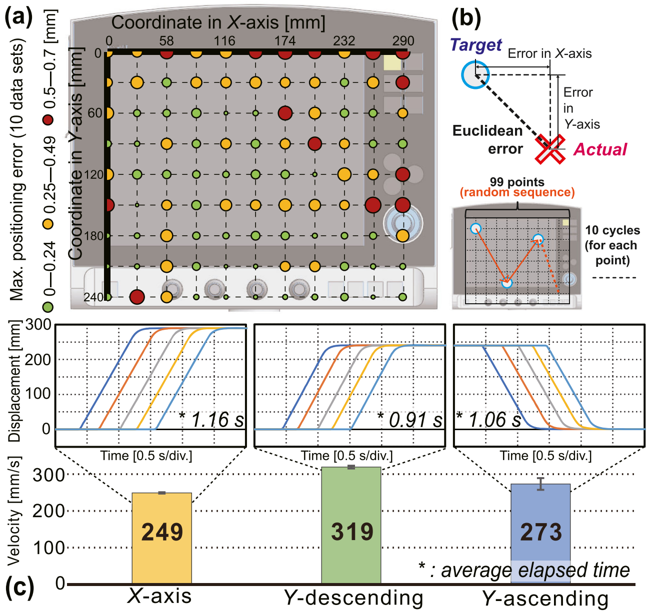

Fig. 4. Experimental results on working performances of XY-positioner. (a) Scatter plot of maximum positioning Euclidean errors for 99 points (10 data sets). (b) Schematics of Euclidean positioning error. (c) Velocity with profiles of each translational motion.

Secondly, translating velocity of the positioner is evaluated based on the long-stroke motion in each axis. The travel range is set as 290 mm for *X*-axis and 240 mm for *Y*-axis. The data acquired from five repeated experiments are averaged and plotted in Fig. 4(c). The descending velocity for the *Y*-axis, ascending velocity for the *Y*-axis, and velocity for the *X*-axis are investigated as 264, 226, and 249 mm/s, respectively. The motion completion time is assessed as 1.16 seconds for the *X*-axis, 0.91 seconds for the *Y*-axis descending, and 1.06 seconds for the *Y*-axis ascending. The liftable weight of the positioner is also measured. The positioner can lift weight less than 1.5 kg in the vertical direction with the same velocity, yet steady-state positioning error increases as weight increases. When the weight of the end-effector (300 g) is lifted, 152 μm of additional positioning error is produced. This value manifests that the end-effector does not degrade the positioning performances of the positioner. Specifications of main performances are listed in Table II.

TABLE II
SPECIFICATIONS OF TCS

XY-Positioner					
Overall size			514 mm (W) × 368 mm (H) × 90 mm (D)		
Weight			3.1 kg (without end-effector)		
			in *X*-axis	**in *Y*-Axis**	**Unit**
Working Performance		**Travel range**	300	250	[mm]
		Resolution	0.0468 (0.16 ‰ F.S.)		[mm]
		Accuracy (Avg. error)	0.099		[mm]
		Repeatability	0.348		[mm]
		Max. velocity	249	273	[mm/s]
		Max. liftable weight	1.5		[kg]
3-DOF End-effector					
Overall size			50 mm (W) × 69 mm (H) × 73 mm (D)		
Weight			300 g		
			Specification	**Required**	**Unit**
Working Performance	**Press in Z-dir.**	**Stroke**	45	27	[mm]
		Velocity	60	-	[mm/s]
		Force	17 <	4	[N]
	Rotation in θ-dir.	**Stroke**	Bi-directional continuous rotation		
		Resolution	0.15	3.75 <	[deg]
		Velocity	210	-	[deg/s]
		***Torque**	26.7	10	[N·mm]

*The specification of the embedded motor.

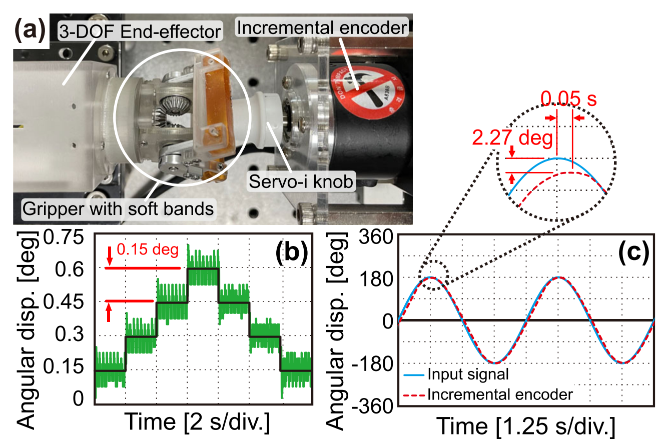

Fig. 5. Experimental results on working performances of the end-effector. (a) Experimental setup. (b) Resolution of rotational motion. (c) Positioning accuracy of rotational motion.

B. Working Performance of 3-DOF End-effector

The key role of the end-effector is to accurately manipulate the user interfaces of therapeutic devices such as touch screens, buttons, and knobs. For the pressing motion of the end-effector, the end-effector can press the physical interfaces in about 1 second with the pressing velocity. In addition, the pressing force is high enough to trigger the input of buttons and touch screen as expressed in Table II. For the gripping motion, the gripper can grip the knobs of the different diameters between 5 and 27 mm. This range is sufficient for the gripper to grip the knobs embedded in the ventilator (i.e., 12.5 mm and 17.5 mm).

For the rotating motion, the end-effector needs to accurately rotate the knobs so that it can follow the rotary input command made by medical staff using the CCS. To investigate the performance for the knob rotation, the experimental bench is set as shown in Fig. 5(a). A commercial incremental encoder (E40S6-3600-6-L-5, *AUTONICS*) is mounted at the front of the end-effector to measure the angular displacement when rotating the knob assembled on the encoder. The angular displacement of the gripper is controlled with a PID controller.

In this experiment, we measure the time-delay and the positioning error under the sinusoidal input in accelerating/decelerating moments. The graph in Fig. 5(c) shows the angular displacement measured by the encoder with the sinusoidal input signal. As presented in the zoomed view, time-delay between the input signal and sensor data is measured as about 0.05 seconds. In addition, the graph shows that the angular positioning error of about 2.27 degrees is produced when the direction of rotation is changed. Second, the experiment on the minimum incremental and decremental step-size is conducted to investigate the positioning resolution. The experimental result plotted in Fig. 5(b) shows the resolution of the end-effector that

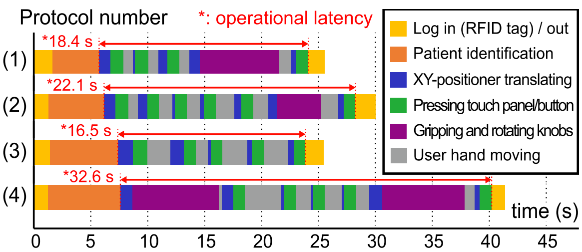

Fig. 6. Tele-operation completion time of selected user scenarios. Protocol number, i.e., (1) to (4), corresponds to minute volume alarm, support mode for apnea, review of event log, and main parameter adjustment, respectively.

is about 0.15 degrees. Considering the experimental results and the resolution of the knobs of ventilator (i.e., 3.75 degrees), it is expected the proposed end-effector can rotate the knobs accurately.

C. Tele-Operation Latency of the Integrated System

We experimentally evaluate the latency of tele-operation, which is a main functional performance of the integrated system. The latency is measured with a system timer of GUI software (Qt Designer 5, *The Qt Company*) which runs inside the control PC of the CCS. The experiment is conducted without using encrypted communication which does not noticeably affect the latency. To make conditions similar to critical situations in ICU, we perform 4 frequent medical protocols: 1. Minute volume alarm 2. Support mode for apnea 3. Review event log 4. Main parameter adjustment. To perform protocols listed above, all physical interfaces are manipulated so that all DOFs of the TCS are used.

From tagging RFID to logging out the CCS, all operations are recorded and categorized as Fig. 6. For all protocols, task completion time is recorded as less than 1 minute. Considering that donning and doffing take more than 10 minutes for medical staff to wear Level D PPE with aid of other medical staff, tele-operation of therapeutic devices can save a large amount of time and labor. The average operational latency of each step was recorded 0.65 seconds for XY-positioner, 1.06 seconds for linear motion of end-effector, 6.43 seconds for the rotating motion of end-effector, and 1.35 seconds for moving a hand to another physical interface. Because the manipulation of knobs comprises all 3-DOF motions (i.e., z-axis pressing, gripping, rotating) generated in series, the operational latency of rotating motion is relatively high.

V. Field Demonstration With Focus Group

To evaluate the performance of our developed system from the viewpoint of medical staff and verify the achievement of medical requirements, we conduct a field demonstration at the simulation center in AMC as shown in Fig. 7(a) to receive direct feedback from the focus group. The focus group consists of 3 medical doctors with careers of 5 to 13 years and 8 registered nurses with careers of 3 to 23 years. Their career is deeply related to treating patients in isolated ICU using the Servo-i ventilator. After a brief introduction and rehearsal of the tele-operated system, we carry out a survey that has 37 questions classified into 4 main evaluation indices: functionality, usability, field applicability, and expandability to other devices. Questions are scored based

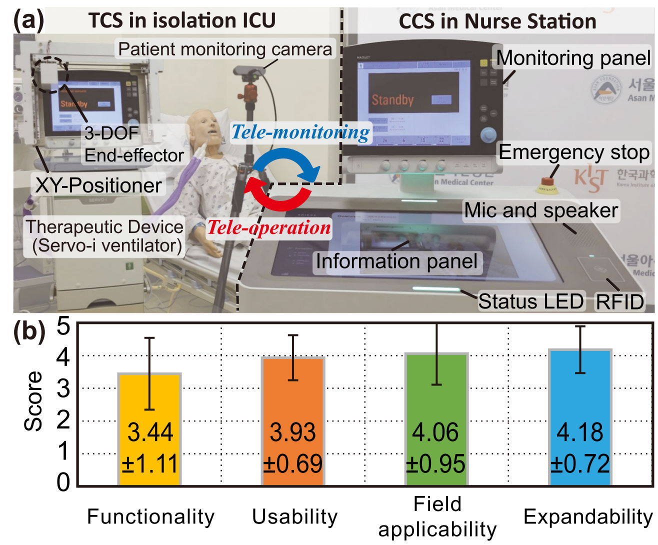

Fig. 7. Field demonstration for the focus group. (a) Experimental setup. (b) The score evaluated by medical staff.

on the 5-point Likert Scale and the results are shown in Fig. 7(b) with the standard deviation of each index.

The first evaluation index is about the functionality of tele-monitoring and tele-operation. The focus group evaluates the functions of the CCS such as information transferability of user interfaces and operating performance of the TCS. The average score of the functionality index is about 3.4 points and the score of the tele-monitoring is higher than that of the tele-operation. The score of remote monitoring is about 3.98, which is positively evaluated by the focus group because the CCS can effectively deliver warning information and help staff to easily identify the patient's condition. The focus group give positive feedback about LEDs and audible alarms because they effectively give warnings to users. On the other hand, the score of the tele-operation is lower because the absence of operational feedback cannot help users to see the current working condition of the TCS. In addition, one of the main feedbacks to improve is the long operational latency of the TCS, which disturbs a fast reaction to emergency situations.

The second evaluation index is the usability of the CCS. The focus group evaluates whether the CCS provides a convenient and friendly manipulating environment to medical staff. Due to the user-friendly user interfaces including the identical shape and position of the monitoring panel, the usability index receives a high score of about 3.93 points. The focus group confirms that the design of the monitoring panel gives a familiar feeling of usage so that they can adapt to the CCS easily. Meanwhile, they mention that the dimension of the CCS would take up a large space in the nurse station so that it can interrupt the movements of medical staff.

The third evaluation index is the field applicability of our developed system to the medical field. In this section, medical staff evaluate whether the system can be applied in ordinary medical environments as well as in the pandemic situation. The focus group gives about 4.06 points with the comment that the system can effectively help the medical staff to treat patients faster than the normal processes with donning and doffing PPE. Moreover, the reduction of frequent wearing of PPE and the time spent in ICU can play a significant role in both pandemic situations and ordinary medical situations.

The last evaluation index is about the expandability of our tele-operation system to other therapeutic devices. The focus group gives a high score of about 4.18 points and evaluates that this system can be effectively applied to other therapeutic devices. The continuous renal replacement therapy (CRRT) device and infusion pump in the isolation ICU are highly expected to be applicable because they are frequently manipulated and have similar interfaces with ventilators.

Based on the survey results, the improvement of the latency during the tele-operation is required for the real-like, fast reaction. In addition, audio-visual feedback that notices whether the tele-operation is in progress or not needs to be implemented. Due to limited space in the nurse station, the size of the CCS should be smaller while delivering sufficient information such as patients' warnings to the medical staff. In addition, the TCS needs to be more precise and accurate for almost zero maloperation. From these improvements, the focus group expects that the upgraded version of our system will be applicable in the medical field and contribute to the medical staff' therapeutic work.

VI. Concluding Remarks

We develop an integrated tele-monitoring/operation system to respond to the urgent needs of medical staff working in isolation ICU. First, we investigate the medical requirements of medical staff and derive the developmental goals about the essential functions that medical staff request. The CCS consists of a monitoring panel that can serve as an intuitive and training-free user interface and an information panel that can support remote controlling the therapeutic device. For the TCS, a precise XY-positioner and compact 3-DOF end-effector are developed to achieve accurate manipulation of the target therapeutic device. The practical performances of the TCS are experimentally investigated. For the XY-positioner, its maximum positioning error and repeatability are observed as 0.695 mm and 0.348 mm, respectively. For the 3-DOF end-effector, the positioning error, time delay, and resolution are measured as 2.27 degrees, 0.05 seconds, and 0.15 degrees, respectively. For the integrated system, the task completion time is recorded as less than 1 minute when executing main medical protocols.

To get direct user-oriented feedback from medical staff, we conduct the field demonstration with the focus group in AMC. Although some functions need to be improved, the focus group expects that our system will serve as a practical device that can alleviate physical and mental burdens and save medical resources. Furthermore, medical staff anticipate the system to be applied to other therapeutic devices frequently used in ICU. Using the proposed design guidelines and functional prototypes to tele-monitor and -operate therapeutic devices, medical staff can treat patients in ICU without risk of infection.

In our future works, we will focus on reducing latency. For XY-positioner, two methods for this would be possible. First, video cameras can be installed upon the CCS to extract the position of the user's finger accessing to the monitoring panel. Based on this approach, it is expected that the position of the end-effector can be synchronized to the finger's position so that the latency of the user's hand moving shown in Fig. 6 is reduced. Second, a therapeutic protocol-based predicting method will be developed. We will record and analyze the general sequence of UI manipulation, thereafter the analyzed result will be used to predict the motion of users.

Additionally, we will implement tele-monitoring function using two camera modules mounted on the TCS. Due to the installed location of cameras, the image homography will be conducted. After that, we will blend the two video sources to minimize the obstructed area blinded by the end-effector. Finally, for practical application to medical fields, we will implement the extended system consisting of a single CCS and multiple TCSs connected via an intranet of the hospital.

References

[1] World Health Organization, "Coronavirus (COVID-19) dashboard," Jun. 2022. [Online]. Available: https://covid19.who.int/

[2] S. M. Abate *et al.*, "Rate of intensive care unit admission and outcomes among patients with coronavirus: A systematic review and Meta-analysis," *PLoS One*, vol. 15, no. 7, Jul. 2020, Art. no. e0235653.

[3] C. Vindrola-Padros *et al.*, "Perceptions and experiences of healthcare workers during the COVID-19 pandemic in the UK," *Brit. Med. J. Open*, vol. 10, no. 11, Nov. 2020, Art. no. e040503.

[4] World Health Organization, "The impact of COVID-19 on health and care workers: A closer look at deaths," Sep. 2021. [Online]. Available: https://apps.who.int/iris/handle/10665/345300

[5] S. Bandyopadhyay *et al.*, "Infection and mortality of healthcare workers worldwide from COVID-19: A systematic review," *Brit. Med. J. Glob. Health*, vol. 5, no. 12, Dec. 2020, Art. no. e003097.

[6] E. Azoulay *et al.*, "Symptoms of burnout in intensive care unit specialists facing the COVID-19 outbreak," *Ann. Intensive Care*, vol. 10, no. 1, Aug. 2020, Art. no. 110.

[7] Y. Shen *et al.*, "Robots under COVID-19 pandemic: A comprehensive survey," *IEEE Access*, vol. 9, pp. 1590–1615, 2021.

[8] Z. Gong *et al.*, "SHUYU robot: An automatic rapid temperature screening system," *Chin. J. Mech. Eng.*, vol. 33, no. 1, pp. 1–4, Dec. 2020.

[9] S. Wang *et al.*, "Design of a low-cost miniature robot to assist the COVID-19 nasopharyngeal swab sampling," *IEEE Trans. Med. Rob. Bionics*, vol. 3, no. 1, pp. 289–293, Feb. 2021.

[10] M. Cardona, F. Cortez, A. Palacios, and K. Cerros, "Mobile robots application against covid-19 pandemic," in *Proc. IEEE ANDESCON*, 2020, pp. 1–5.

[11] A. Zemmar *et al.*, "The rise of robots in surgical environments during COVID-19," *Nature Mach. Intell.*, vol. 2, no. 10, pp. 566–572, Oct. 2020.

[12] N. Feizi *et al.*, "Robotics and AI for teleoperation, tele-assessment, and tele-training for surgery in the era of COVID-19: Existing challenges, and future vision," *Front. Robot. AI*, vol. 8, Apr. 2021, Art. no. 610677.

[13] A. Giusti *et al.*, "BALTO: A BIM-Integrated mobile robot manipulator for precise and autonomous disinfection in buildings against COVID-19," in *Proc. IEEE 17th Int. Conf. Automat. Sci. Eng.*, 2021, pp. 1730–1737.

[14] R. Tsumura *et al.*, "Tele-Operative low-cost robotic lung ultrasound scanning platform for triage of COVID-19 patients," *IEEE Rob. Autom. Lett.*, vol. 6, no. 3, pp. 4664–4671, Jul. 2021.

[15] F. Garzotto *et al.*, "Preventing infectious diseases in intensive care unit by medical devices remote control: Lessons from COVID-19," *J. Crit. Care*, vol. 61, pp. 119–124, Feb. 2021.

[16] G. Yang *et al.*, "Keep healthcare workers safe: Application of teleoperated robot in isolation ward for COVID-19 prevention and control," *Chin. J. Mech. Eng.*, vol. 33, Jun. 2020, Art. no. 47.

[17] B. P. Vagvolgyi *et al.*, "Telerobotic operation of intensive care unit ventilators," *Front. Robot. AI*, vol. 8, Jun. 2021, Art. no. 612964.

[18] W. Murk *et al.*, "Diagnosis-wide analysis of COVID-19 complications: An exposure-crossover study," *Can. Med. Assoc. J.*, vol. 193, no. 1, pp. E10–E18, Dec. 2020.

[19] A.-S. Poncette *et al.*, "Patient monitoring alarms of an intensive care unit: Observational study with DIY instructions (Preprint)," *J. Med. Internet Res.*, vol. 23, no. 5, Dec. 2020, Art. no. e26494.

[20] Korea health insurance review & assessment service. "Detailed status of medical devices," Feb. 2022. [Online]. Available: https://hira.or.kr

[21] J. W. Comb, "Gantry assembly for use in additive manufacturing system," US Patent, US9108360B2, Aug. 2015.

[22] Manipulating industrial robots – Performance criteria and related test methods, *ISO 9283*,1998.